ENERGY INTEGRATION

IN SPONGE IRON PLANT USING HEAT OF WASTE GAS

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by

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CERTIFICATE

This is to certify that the thesis entitled “Energy integration in sponge iron plant using heat of waste gas” being submitted by Annavajhala Mrudula as an academic project in the Department of Chemical Engineering, National Institute of Technology, Rourkela is a record of bonafide work carried out by her under my guidance and supervision.

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ABSTRACT

Direct-reduced iron (DRI), also called sponge iron, is produced from direct reduction of iron ore (in the form of lumps, pellets or fines) by a reducing gas produced from natural gas or coal. Unlike the conventional process, the process does not require coking coal; the coke ovens in a steel plant are expensive and polluting units. Direct reduction, has been developed to overcome these difficulties of conventional blast furnaces.

In the present work a system is designed to integrate the heat of waste gas in the sponge iron process. For this purpose a case study of typical sponge iron production process is considered. Waste gas from the rotary kiln of the sponge iron plant exits at a temperature around 900 °C. This gas has a lot of sensible heat and can be used for energy integration. This heat is used for heating water in a boiler. Superheated steam which is produced in the boiler is used to rotate a prime mover like a steam turbine. The objective in the project is to design a system that will utilize waste heat from the process.

For this design total power generation of 10.77 MW was found using steam turbine. The annual profit upon incorporating the design was found to be Rs 411 lakhs when the power generated is exported for use. The payback period for this system is 1.22 years.

Keywords: Waste heat, Energy integration, Steam turbine

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CHAPTER 1

INTRODUCTION

Sponge iron, also known as direct reduced iron, is produced from iron ore below the fusion temperature of iron ore, 1535 °C. Unlike the conventional methods involving blast furnaces, the iron ore is directly reduced in the solid form, and hence the process is termed as 'direct reduction'. The reducing gas is a mixture of hydrogen and carbon monoxide, which acts as the reducing agent. The metallic mass is called a sponge because of its appearance – a honey comb structure with minute holes all over the surface and bulk. Sponge iron is produced primarily both by using non coking coal and natural gas as reductant and therefore classified as coal based and natural gas process respectively. Presently, there are 118 large and small sponge iron plants in India- 115 of them are coal based while only 3 are natural gas based.

The advantages of sponge iron are:

- Chemical composition is known exactly
- Chemical composition is uniform
- Contains no undesirable metallic impurities
- Permits dilution with low cost

These advantages of sponge iron make it a preferred product over iron produced from blast furnaces. Further, easy availability of raw materials and less payback period have turned the sponge iron industry into a profitable venture. However, lately the industry is facing a setback in the market due to lack of proper integration techniques and proper heat utilization methods. A lot of heat generated in the process is vented to the atmosphere without being recovered. Eriksson et al studied the energy survey of the sponge iron process and showed that the process is 40% efficient and the exhaust gases are responsible for the majority of the heat loss [1]. Biswas et al found that 10-12 % energy can be saved by controlling radial and axial air injection, which will lead to efficient combustion and improved heat transfer [2]. Jena et al worked on the kiln data at OSIL and showed that the thermal efficiency of the process is 51. 315 %. [3] About 33% of the heat generated in the kiln is lost in the waste gas. The above fact has also been reiterated by many investigators. [4], [5]

From the above discussion it may be concluded that it has become imperative to design new integration techniques to overcome all the shortcomings in the process. High temperature waste sources which are available which can be utilized in the Steam Rankine Cycle. For this purpose the following objectives have to be reached:

1. To identify areas in the process where energy integration may be carried out.
2. To design systems that will utilize the waste heat.
3. To perform economic analysis of the proposed design based on capital costs, water consumption, payback period, etc.

CHAPTER 2

LITERATURE REVIEW

2.1. DRI PROCESS OF SPONGE IRON MAKING

2.1.1 Introduction

The production of steel began in ancient times; but because of the complexity and slow speed of the ancient process, they could not be carried out on a very large scale. Consequently, they were replaced by the high production rate ‘indirect process’, and the development of modern DR process did not begin until the middle of 19th century. Perhaps the very first patent in U.K. for sponge iron making was in 1972 presumably using a rotary kiln. More than 100 DR processes have been invented and operated since 1920. Most of these have died down but some of them have re-emerged in slightly different form. [6]

Sponge iron is mainly produced from iron ore by two different routes – (a) - by reducing gases (CO and H_2) in a shaft furnace, and (b) through direct treatment with coal in a rotary kiln.

The conventional route for making steel consists of sintering or pelletization plants, coke ovens, blast furnaces, and basic oxygen furnaces. Such plants require high capital expenses and raw materials of stringent specifications. Coking coal is needed to make a coke strong enough to support the burden in the blast furnace. Integrated steel plants of less than one million tons annual capacity are generally not economically viable. The coke ovens and sintering plants in an integrated steel plant are polluting and expensive units. Direct reduction, an alternative route of iron making, has been developed to overcome some of these difficulties of conventional blast furnaces. DRI is successfully manufactured in various parts of the world through either natural gas or coal-based technology. Iron ore is reduced in solid state at 800 to 1,050 °C (1,472 to 1,922 °F) either by reducing gas (H_2+CO) or coal. The specific investment and operating costs of direct reduction plants are low compared to integrated steel plants and are more suitable for many developing countries where supplies of coking coal are limited. [7]

2.1.2. Raw Materials

Table 2.1: Raw Materials for Production of Sponge Iron

Material	**Size**
Iron Ore	5-18 mm
Coal	3-20 mm
Dolomite	2-6 mm
Air	-

2.1.3. Theory

In any rotary kiln process based on coal, the reduction of iron oxide takes place by the carbon monoxide produced from coal. The following reactions involved are as follows:

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$$

$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2$$

$$FeO + CO \rightarrow Fe + CO_2 \quad [8]$$

2.1.4. Commercial Processes

The processes, which are currently in vogue, are SL/RN Process, Jindal Process, SIL Process, Krupp- Codir Process and TDR Process. SIL Process is based on the Lurgi or the SL/RN Process.

2.1.4.1. SL/RN Process

- The raw materials (iron ore, coal and dolomite) are charged into the rotary kiln with the help of conveyor.
- Compressed air is injected into the rotary kiln at various places with the help of blowers.
- The temperature of the charge bed inside the kiln is limited to a maximum of around 950-1050 °C so that the ash in coal does not fuse. As a result, the entire reduction occurs in the solid state.
- A finer fraction of coal is also normally injected from the discharge end of the kiln. This helps complete the reduction and supply heat as a result of combustion.
- A flux (like dolomite or limestone) has to be added along with coal in order to control the sulphur pick up by the reduced material from coal ash.
- The residence time of iron ore inside the kiln is about 10 hours. After being discharged, the materials enter a rotary cooler where their temperature is brought down to 120°C.
- The reduced iron oxide is separated from char and other non-magnetic portions using magnetic separators.
- The products are then screened and sent for storage. The gases out of the rotary kiln are burnt in a chamber to ensure that CO is negligibly present. The gases at 1000 °C enter the ESP from where they are routed to the atmosphere through a chimney at 200-250 °C.

The flow sheet for a SL/RN process is shown in figure 2.1. [9]

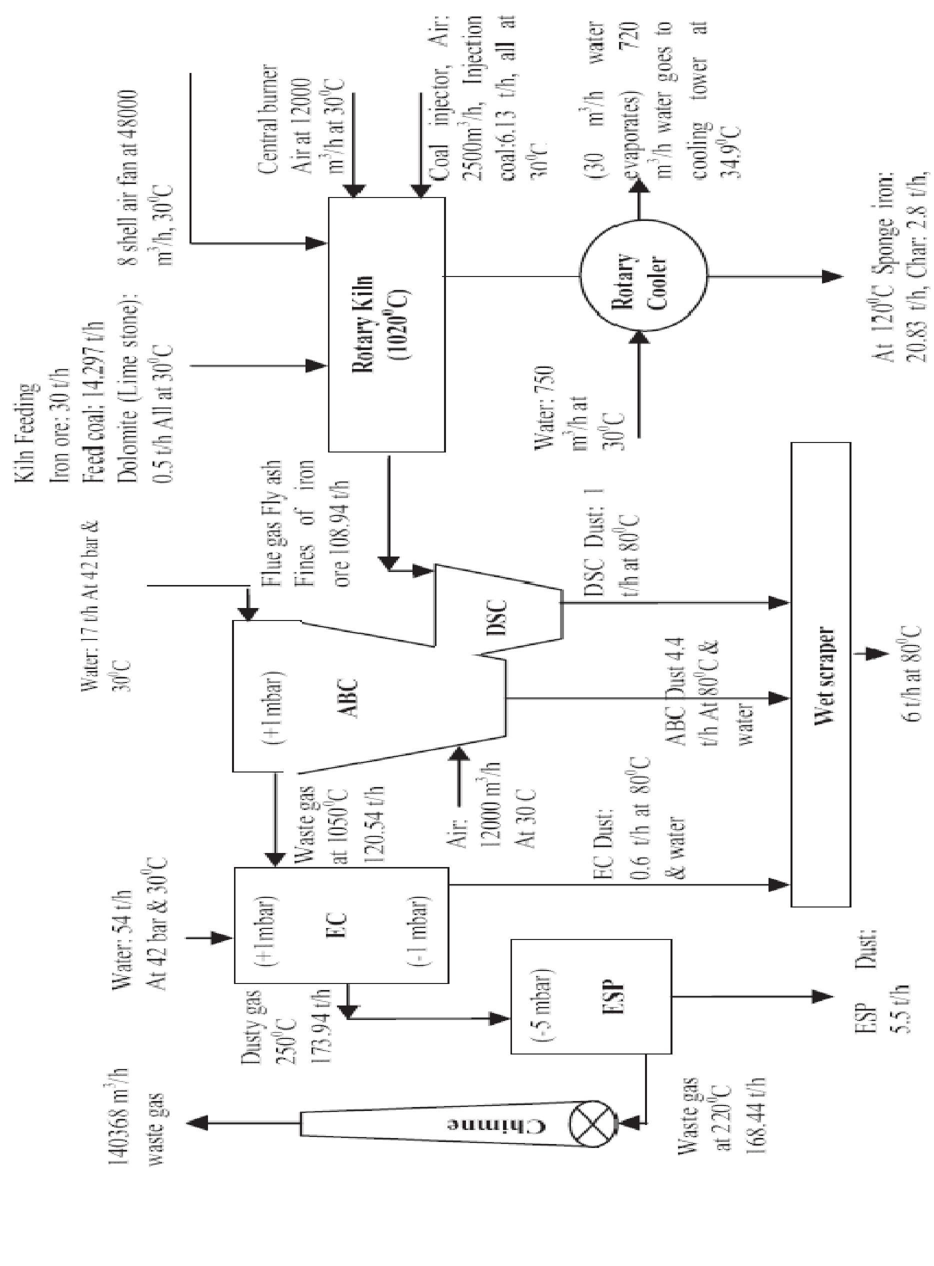

Figure 2.1: Conventional sponge iron plant flow diagram

2.1.4.2. Jindal Process

- This process was developed by Jindal Strips Ltd.
- The unique feature is that 55-60% coal is injected from discharge end and rest with ore injection.
- The C/Fe ratio is around 0.42-0.44.
- Coal up to 30% ash content is successfully used.
- Blast furnace gas has been used in this process and has resulted in better reduction.
- Steam is produced by utilization of waste heat.
- The char and coal washery rejects are used in fluidized bed combustion boiler and results in better waste heat recovery.

2.1.4.3. Codir Process

- Codir stands for Coal Ore Direct Reduction process.
- It is very similar to SL/RN process with minor modifications.
- The coal size range is very coarse (5-35 mm), which is a unique feature of Codir. Coal is counter currently injected into the rotary kiln.
- The air inlets are positioned towards the inlet end of rotary kiln.
- Codir coolers use direct mist of water inside the cooler.

2.1.4.4. Accar Process

- This standsfor Allis- Chalmers Controlled Atmospheric Reduction.
- The process is similar to SL/RN and Codir processes.

- The fundamental difference is that, the reductant used in the process is a mixture of coal+ oil or coal + natural gas.
- Oil/gas is injected directly in radial ports, symmetrically arranged in rows.
- The injection is maintained in such a manner that, when the ports are under charge, oil/gas is injected and when the ports are over the bed, air is injected.
- The advantages are higher carbon content, high degree of metallization, low energy consumption, low operating temperatures, etc.

2.1.4.5. TDR Process

- TDR stands for TISCO Direct Reduction process and was developed in India.
- Only non- coking coal is used and reductant and fuel oil is used only for kiln preheating.
- Coal used is of a specified size range and injected from both sides.
- Dolomite is used in a specific size range.
- Provision for radial and axial injection of air exists.
- Rotary kiln has a diameter of 3.75m and length of 72m, inclination is 1.432°.

2.1.5. Advantages of DRI Process:

- The energy requirements of a sponge iron plant are much less than a conventional blast furnace plant.
- The process does not require coking coal or coke.
- The product, hot briquetted iron, is a compact form of DRI designed for ease of transportation.

- The percentage of iron is generally more than pig iron.
- The operating costs are low too.

2.2. BOILER

2.2.1. Introduction

A steam generator or boiler is a device used to generate steam by applying heat energy to water.. A boiler contains a firebox or furnace which is used for burning the fuel and generating heat; this produces saturated steam. The higher the temperature of furnace, the faster is the steam production. The saturated steam thus produced can then either be used immediately to produce power via a turbine and alternator, or else may be further superheated to a higher temperature; this notably reduces suspended water content making a given volume of steam produce more work and creates a greater temperature gradient in order to counter tendency to condensation due to pressure and heat drop resulting from work plus contact with the cooler walls of the steam passages and cylinders. [10]

2.2.2. Waste heat recovery boilers

Waste heat recovery boilers or heat recovery steam generators form an inevitable part of chemical plants, refineries and process systems. They are mainly classified based on whether the boiler is used for energy recovery or for process purposes. Waste heat boilers are used to cool waste gas streams from a given inlet temperature to a desired exit temperature for further processing. In energy recovery applications, the gas is cooled as much as possible while avoiding low temperature corrosion. Examples can be found in flue gas heat recovery from furnaces, incinerators and kilns. The objective here is to maximize energy recovery.

A common classification of boilers is as follows:

1. Fire tube boilers
2. Water tube boilers

If the hot combustion gases are restricted to inside the tubes and the tubes are surrounded with water, the boiler is a fire tube boiler while if the arrangement is opposite, i.e., water is inside the tubes and hot gases are outside the tubes, the boiler is a water tube type.Generally water tube boilers are used for electric power stations.

Fire tube boilers have low initial cost, are more compact but are more likely to explode. Further, because of water volume being more and circulation being poor they cannot meet quickly the changes in steam demand. For the same output, the outer shell of a fire tube boiler is much larger than that of a water tube boiler.

Water tube boilers have less weight of metal for a given size, are less liable to explosion, produce higher pressure, are easily accessible and can respond quickly to changes in steam demand. Tubes and drums of water tube boilers are smaller than those of fire tube boilers. Whereas the maximum working pressure in a fire tube boiler is limited to only 17 kg/cm^2 gauge, pressures as high as 125kg/cm^2 gauge and temperatures from 315°C to 575°C are attainable with water tube boilers. [11] Water tube boilers require lesser floor space. Figure 2 shows a typical water tube boiler. [12]

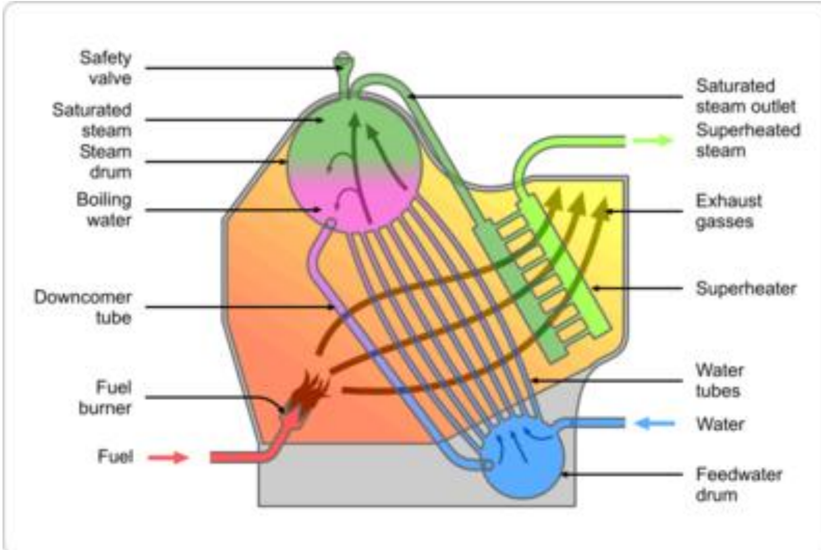

Figure2.2: Water tube boiler

2.3. STEAM TURBINE

2.3.1. Introduction

A steam turbine is a mechanical device that is used to extract thermal energy from pressurized steam. It operates on basic principles of thermodynamics using a part of the Rankine cycle. In a steam turbine, superheated vapour enters the turbine at high temperature and pressure. The steam is converted into kinetic energy using a nozzle. After the steam exits the nozzle it moves at a high velocity and goes to the blades of the turbine. A force is created on the blades of the turbine due to the pressure of the vapour on the shaft. The gas exits the turbine as a saturated vapour at a lower temperature and pressure and enters a condenser where it is cooled to its liquid state. The process of condensing steam created a vacuum, which then brings in more steam from the turbine. The water is returned to the boiler, reheated and used again.

Steam turbines are broadly classified into three types: impulse, reaction, and combined (impulse-reaction), depending upon the way in which the transformation of potential energy into the kinetic energy of a steam jet is achieved. [13]

2.3.2 Design of Steam Turbine

The simple single disc steam turbine consists of the following principle parts:

- Expansion nozzle
- Shaft
- Disc
- Blades

The shaft along with the disc mounted upon it comprises the most important part of the turbine and is known as the rotor, which is housed in the turbine casing. The journals of the shaft are placed in bearings which are located in the base of the turbine casing.

In turbines of these types, the expansion of the steam is achieved from its initial pressure to its final one in a single nozzle or a group of nozzles situated in the turbine stator and placed in front of the blades of the rotating disc. The decrease of steam pressure in the nozzles is accompanied by a decrease of its heat content, this decrease of heat content achieved in the nozzles subsequently accounts for the increase in the velocity of the steam issuing from the nozzles. The kinetic energy of the steam jets exerts an impulse force on the blades and performs mechanical work on the shaft of the turbine rotor.

The turbines in which the complete process of expansion of steam takes place only in stationary nozzles, and the kinetic energy is transformed into mechanical work on the turbine blades (without any further expansion taking place in them) are known as impulse turbines. Steam velocity at the exit of the nozzles in such turbines reaches a value of about 1200 m/s and over. [14]

Those turbines, in which the expansion of steam takes place not only in the passage of the guide blades but also in the moving blades, so that the overall decrease in heat content in all the stages is, more or less, uniformly distributed between them, are known as reaction turbines.

2.3.3 Velocity Diagram for Impulse Turbines

As we know, the main parts of an impulse turbine are the nozzles and blades. The steam is utilized in the nozzles to produce a jet of steam moving with high velocity. The function of blades is to change the direction of the high velocity steam and hence the momentum of the jet or jets of steam so as to produce a force which propels the blades. As this propelling force is due to a change of momentum caused mainly by the change in the direction of flow of the steam, it is essential to draw the diagrams showing the variation of steam during its flow through the blade passages. [15]

It is an established fact that velocity is a vector quantity. It has (a) magnitude, (b) direction and (c) sense of direction. Thus we can represent velocity by a straight line and indicate (a) its magnitude by the length of the straight line to a suitable scale (b) its direction by the direction of the said straight line with reference to some fixed direction and (c) its sense of direction by an arrow placed on the straight line. Figure 2 shows a velocity vector diagram for a steam turbine.

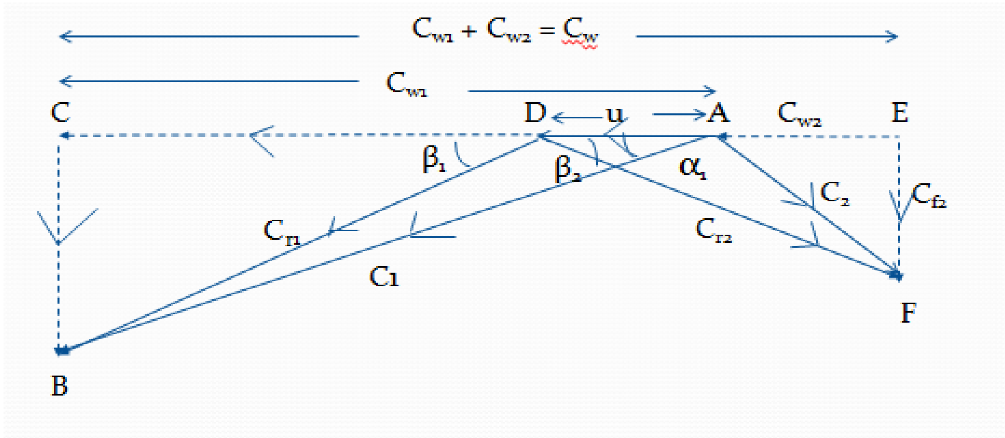

Figure 2.3: Velocity Vector Diagram for a steam turbine

Where,

- C_1= absolute velocity of steam at inlet to moving blade, i.e., exit velocity of nozzle
- C_2= absolute velocity of steam at outlet from the blade
- C_{r1}= relative velocity of steam with respect to the tip of the blade at inlet
- C_{r2}= relative velocity of steam with respect to the tip of the blade at outlet
- C_{w1}= tangential component of velocity C_1 known as velocity of whirl
- C_{w2}= tangential component of velocity C_2
- u= velocity of blade (mean value)
- β_1= angle of blade at inlet
- β_2= outlet angle of blade
- α_1= angle made by entering steam having velocity C_1 with tangent of the wheel at entrance of moving blade

- α_2= angle to the tangent of wheel at which C_2 leaves the blades

2.4. GAS TURBINE

2.4.1 Introduction

The gas turbine obtains it power by utilizing the energy of high temperature burnt gases and air by expanding through fixed and moving blades. A gas turbine cycle consists of:

1. a compressor
2. a combustion chamber
3. a turbine

The compressor is coupled with the turbine shaft and so absorbs some of the energy produced by the turbine which lowers its efficiency. Hence the net work done by the turbine is the difference between the turbine work and the work required by the compressor.

Gas turbines may be classified on the basis of the following:

(a) on the basis of combustion process:

1. Continuous combustion or constant pressure type: this type of turbine works on the basis of Joule or Brayton cycle.
2. Explosion or constant volume type: this type of turbine is based on the Atkinson cycle.

(b) On the basis of the action of expanding gases similar to steam turbine:

1. Impulse turbine
2. Impulse reaction turbine

(c) On the basis of path of working substance:

1. Open cycle gas turbine (working fluid enters from atmosphere and exits from atmosphere)
2. Closed cycle gas turbine (working fluid is confined within the plant)
3. Semi closed cycle (part of the working fluid is confined within the plant and another part flows from and to the atmosphere)

(d) On the basis of direction of flow

1. Axial flow
2. Radial flow [15]

2.4.2 Comparison of Steam Turbines and Gas Turbines

The advantages of a gas turbine are:

(i) No feed water supply is required

(ii) There is no need of a condensing plant

(iii) Boiler is not required

(iv) The maintenance cost is low.

(v) It has lower specific weight and size, i.e., lower weight and size per KW output.

(vi) It has lower operating pressure

Disadvantages:

(i) The power developed is less than steam turbine because of the power consumed by the compressor.

(ii) The thermal efficiency is lower.

CHAPTER 3

PROBLEM STATEMENT

3.1 CASE STUDY

The present work is based on the data of a typical sponge iron production plant with an overall capacity of 200 tpd. The following data was collected to carry out the work.

3.1.1 Feed Stream

The feed mix fed into the rotary kiln is if specific size and composition which has been shown in Table 3.1.

Table 3.1: Feed Stream Properties

Raw Material	Source	Particle size (mm)	Feed temperature (°C)	Flow rate (tph)
Iron Ore	Barbil	5-18	30	30
Coal	M.C.I	<18	30	14.297
Dolomite	Chattisgarh	2-6	30	0.5

3.1.2 Dust Settling Chamber

The flue gas from the rotary kiln goes to the dust settling chamber from where the dust is separated. The properties of the gas at inlet and outlet are shown in Table 3.2

Table 3.2: Gaseous Stream at Dust Settling Chamber

Inlet Temperature (°C)	Outlet Temperature (°C)	Flow rate (tph)
900- 950	900- 950	108.94

3.1.3 After-Burning Chamber

In the after-burning chamber, the residual CO is burnt. The properties of the flue gas stream are shown in Table 3.3

Table 3.3 Gaseous Stream at After- Burning Chamber

Inlet Temperature (°C)	Outlet Temperature (°C)	Flow rate of exit stream (tph)
900 -950	850 -900	120.54

3.2 FLOW SHEET

The flow sheet of a typical sponge iron plant with material and energy is shown in Figure 3.1

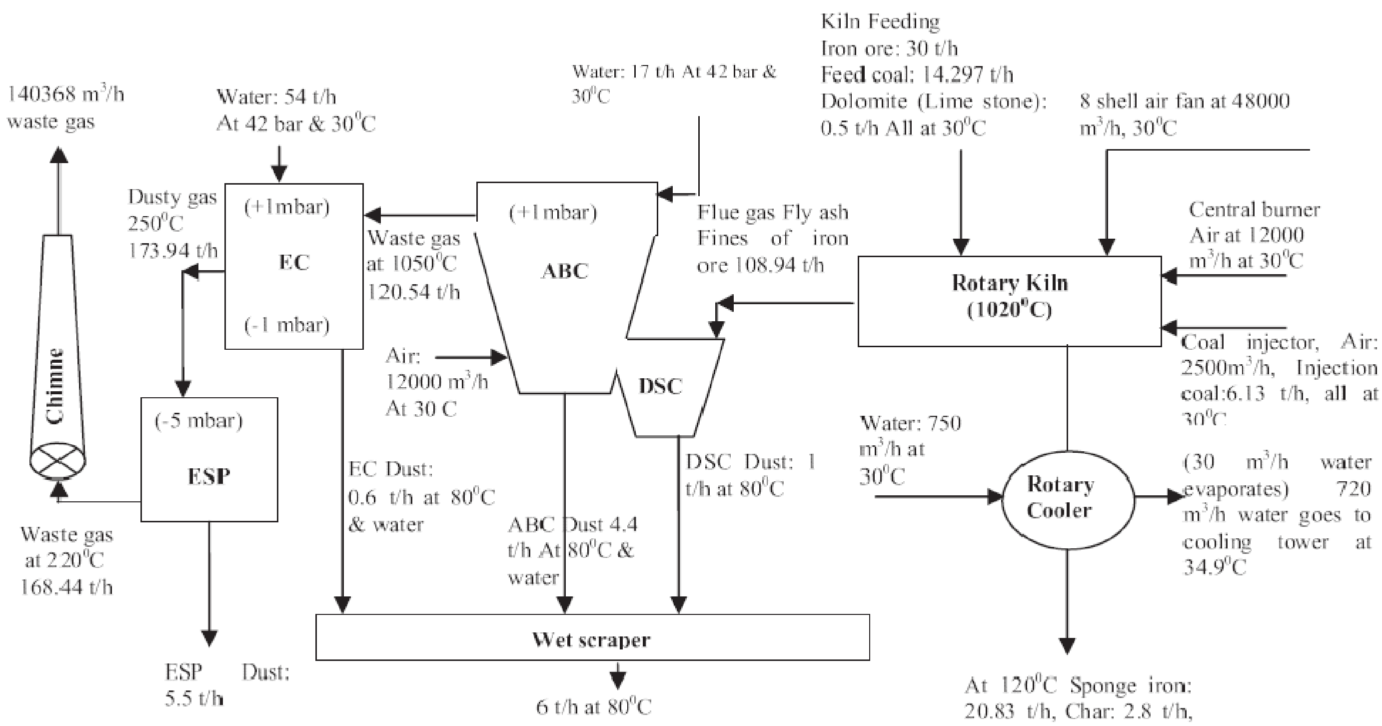

Figure 3.1: Process flow sheet showing area for energy integration

3.2.1. Process Description

The sponge iron production process is described through following points:

- The raw materials (iron ore, coal and dolomite) are charged into the rotary kiln with the help of conveyor.
- Compressed air is injected into the rotary kiln at various places with the help of blowers.

- The temperature of the charge bed inside the kiln is limited to a maximum of around 950-1050 °C so that the ash in coal does not fuse. As a result, the entire reduction occurs in the solid state.
- A finer fraction of coal is also normally injected from the discharge end of the kiln. This helps complete the reduction and supply heat as a result of combustion.
- A flux (like dolomite or limestone) has to be added along with coal in order to control the sulphur pick up by the reduced material from coal ash.
- The residence time of iron ore inside the kiln is about 10 hours. After being discharged, the materials enter a rotary cooler where their temperature is brought down to 120°C.
- The reduced iron oxide is separated from char and other non-magnetic portions using magnetic separators.
- The products are then screened and sent for storage. The gases out of the rotary kiln are burnt in a chamber to ensure that CO is negligibly present. The gases at 1000 °C enter the ESP from where they are routed to the atmosphere through a chimney at 200-250 °C.

3.3 AREAS OF INTEREST FOR ENERGY INTEGRATION

From the flow diagram, shown in Fig. 3.1, it may be observed that the waste gas from the after-burning chamber goes to the Evaporating Chamber where it is quenched and the temperature of the gas is brought down from 900 °C to a workable limit for downstream equipment. This gas is then vented through a chimney to the atmosphere. Hence, the idea in the project is to utilize the heat from the waste gas coming from the after-burning chamber by using a waste heat boiler connected to a steam turbine, which is used for power generation.

CHAPTER 4

ENERGY INTEGRATION METHODS

4.1 POTENTIAL AREAS FOR ENERGY INTEGRATION

The area where energy is to be conserved is the Evaporating Chamber where flue gas enters at a temperature of 850-900°C and leaves at 250°C. This heat in the gas can be utilized before the gases are vented to the atmosphere.

The idea proposed in this project is to use the waste heat from the flue gas to heat water in a waste heat recovery boiler. The steam produced is directed to a steam turbine using which power can be generated.

Hence, the new system will consist of:

1. Waste heat recovery boiler
2. Steam turbine

4.2 DESIGN PROCEDURE

4.2.1 Waste heat boiler

In the boiler, steam is produced using the waste heat from the gas. The flue gas enters the boiler around 850 -900 °C and leaves at 250 °C. The pressure in a water tube boiler is as high as 125kg/cm^2 gauge and temperatures vary from 315°C to 575°C. Energy balance was carried out to determine the flow rate of steam produced. The efficiency of the boiler was assumed to be 85%.

So we have,

$$m_g C_g \Delta T g = m_s\,(\lambda + C_{p1}(T_s - T_0) + C_{p2}(T_{out} - T_s)$$

Where, m_g and $m_s$are the gas and steam flow rates respectively

C_g, C_{p1} and C_{p2} are the specific heats given by the formula:

C_p =1.78+(0.107T)+(0.586T^2)-(0.2T^3)

λ is the latent heat of vaporization of water at the specified pressure

T_s is the saturation temperature of water at the specified pressure

T_0 is the ambient temperature

T_{out} is the outlet temperature of steam

$\Delta T_g$is the temperature difference between inlet and outlet gas temperature

4.2.2. Steam turbine design [16]

- From steam tables, inlet conditions- enthalpy H_1 and entropy S_1 at the given temperature and pressure are specified.
- Turbine outlet conditions – pressure P_2 for temperature $T_2$is found out from steam tables. As isentropic expansion takes place, Entropy S_2 is same as S_1.
- The wetness fraction (X) can be calculated from

$$S_2 = XS_L + (1-X)\,S_V$$

where S_L and S_V are the saturated liquid and vapour entropies at T_2 and P_2. Taking saturated liquid and vapour entropies from steam tables at T_2 and $P_{2,}$ the turbine outlet enthalpy for an isentropic expansion can be calculated from

$$H_2 = XH_L + (1\text{-}X)\ H_V$$

Where H_L and H_V are the saturated liquid and vapour enthalpies.

- For a single stage expansion with isentropic efficiency of η

$$H_2' = H_1 - \eta\ (H_1 - H_2)$$

- The actual wetness fraction (X') can be calculated from:

$$H_2' = X'H_L + (1\text{-}X')\ H_V$$

Where H_L and H_V are the saturated liquid and vapour enthalpies

4.2.3. Design Procedure for Single Stage Impulse Turbines

Following data is to be known prior to the designing of a single stage impulse turbine:

1. Generator output
2. Pressure and temperature at the inlet to the turbine, (p_0, t_0)
3. Back pressure of steam, $p_{2.}$

The sequence of calculation is as follows: [15]

- The isentropic heat drop $(\Delta h)_{isen}$is obtained between pressure p_0 and $p_{2.}$
- The velocity at the exit of the nozzle is calculated from C_1=sqrt $((\Delta h)_{isen})$
- The nozzle angle may be assumed between the limits of 14 to 20 degrees.

- For various values of u/C_1, the approximate internal efficiency is calculated using the equation,

$$\eta_i = \eta_b - \frac{(P_{loss})\Delta_{f,bw}}{C_1^2/2}$$

Plotting a graph between η_i and (u/C_1), $(\eta_i)_{max}$ and $(u/C_1)_{optimum}$ are found.

- With $(u/C_1)_{optimum}$, u and diameter D of the disc are calculated.
- Velocity triangles are drawn and the various losses and η_i are determined by using calculated reheat factor (RF) and stage efficiency (η_s) values.

4.3. COST ESTIMATION

The annual cost consists of fixed costs and operating costs.

Capital Costs:

Capital cost= Cost of boiler + steam turbine

Annual fixed costs = Capital cost/ Service life

Operating Cost:

Annual operating cost= Cost of (water+ equipment maintenance)

If power generated is exported, then annual earnings = cost of electricity exported

Annual savings = cost of electricity exported – annual operating cost

If power consumption by equipment is R,

Annual savings = Cost of electricity exported- R- annual operating cost

Payback period = Capital cost/ Annual savings

All these steps of design of waste heat recovery boiler and steam turbine along with economic analysis as described in Appendices A to D.

CHAPTER 5

RESULTS AND DISCUSSION

5.1. DESIGN OF BOILER

The mass flow rate of steam that could be produced by using the heat in the waste gas was calculated. The efficiency of the waste gas fired boiler was taken to be 85% [1]. In the boiler, the pressure in the boiler was taken as 9,000 kPa and temperature of 500°C.Using energy balance, the steam flow rate was found out as shown in table 5.1.

Table 5.1: Boiler specifications

Mass rate of flue gas	120.54 t/h
Specific heat	1.66 KJ/kg
Inlet temperature	900 °C
Exit temperature	100°C
Superheat temperature of water	550°C
Specific heat during superheat	2.062 KJ/kg
Mass rate of steam produced	12.34 kg/sec

The steam produced from the boiler is used for power generation using a steam turbine, as explained in section 5.2.

5.2. DESIGN OF STEAM TURBINE

The steam produced in section 6.1 was used for the design of a single stage, impulse steam turbine. The thermal efficiency of the turbine was calculated for different values of steam outlet temperature and pressure and the values giving the highest efficiency were chosen. . The temperature of the flue gas from the rotary kiln varies between 850-900 °C. Iterations were carried out for flue gas temperatures of 850 °C and 900 °C, at pressuresof 9000 kPa and 8000 kPa and various values of steam inlet and outlet temperatures. The calculations for a pressure of 9000 kPa and a gas temperature of 850 °C are shown in Table 5.2.

Table 5.2: Iterations for pressure of 9000 kPa and gas temperature of 850 °C

steam inlet Temp (°C)	gas inlet temp (°C)	steam outlet temp (°C)	ms (kg/sec)	Wetness fraction (x)	power generated (kW)	Overall thermal efficiency ηoth
350	850	150	14.11871074	0.119659	7054.895079	0.21229178
350	850	140	14.11871074	0.129593	7584.532952	0.22414951
350	850	130	14.11871074	0.139579	8133.781826	0.23619466
350	850	120	14.11871074	0.149705	8703.429814	0.24844563
350	850	110	14.11871074	0.160066	9294.808856	0.26093505
350	850	100	14.11871074	0.170778	9909.972737	0.27371359

From the above iterations, it was observed that when the steam inlet temperature was fixed, the efficiency was highest for a steam outlet temperature of 100 °C. Hence, for further calculations, only steam outlet temperature of 100 °C was used as shown in table 5.3.

Table 5.3: Iterations at 9000 kPa for different values of steam inlet temperature

400	850	100	13.43585169	0.128891	9847.647238	0.27247405
450	850	100	12.8070946	0.090959	9898.603244	0.27451585
500	850	100	12.22625027	0.056148	10024.35058	0.27877769
550	850	100	11.68806237	0.023861	10199.06347	0.28454836

From these iterations, the thermal efficiency was found to be the maximum for a pressure of 9000 kPaand a temperature of 550 °C. The mass flow rate of steam was found to be 11.68 kg/sec and the power generated as 10.19 MW.

Further calculations were performed to test the effect of pressure and gas inlet temperature on the efficiency as shown in Tables 5.4 and 5.5.

Table 5.4: Iterations for a pressure of 8000 kPa and gas inlet temperature of 850 °C

Steam inlet Temperature (°C)	Gas inlet temperature (°C)	Steam outlet temperature (°C)	ms (kg/sec)	Wetness fractionX'	Power generated (KW)	Overall thermal efficiency ηoth
350	850	100	13.69250535	0.170778	9610.817672	0.273607
400	850	100	13.04933305	0.128891	9564.353006	0.272373
450	850	100	12.4554612	0.090959	9626.825794	0.274418
500	850	100	11.90542425	0.056148	9761.304074	0.278683
550	850	100	11.39455818	0.023861	9942.950196	0.284456

It was observed that the thermal efficiency was almost the same for pressures of 9000 kPa and 8000 kPa (0.28 in both the cases). However, power generated in the first case was 10.2 MW while in case of the latter it is 11.69 MW and also since usually, lower pressures are easy to attain in equipment, we prefer a pressure of 8000 kPa for further designing. It may be noted that the wetness fraction of steam was found to be 0.02 which is much below the maximum allowable limit of 0.15. [16]

Similar calculations were performed for gas inlet temperature of 900 °C. The results are summarized in table 5.5.

Table 5.5: Turbine calculations for flue gas temperature of 900 °C and pressure of 9000 kPa

Steam inlet temperature (°C)	Gas inlet temperature (°C)	Steam outlet temperature (°C)	Steam mass flow rate ms (kg/sec)	Wetness fraction X'	Power generated (KW)	Overall thermal efficiency ηoth
350	900	100	14.11871074	0.170778	9909.972737	0.27371359
400	900	100	13.43585169	0.128891	9847.647238	0.27247405
450	900	100	12.8070946	0.090959	9898.603244	0.27451585
500	900	100	12.22625027	0.056148	10024.35058	0.27877769
550	900	100	11.68806237	0.023861	10199.06347	0.28454836

Next, the variation of the overall thermal efficiency with the pressure of inlet steam was studied by taking a pressure of 8000 kPa. Further, for this pressure, the effect of gas inlet temperature was found out. The results are summarized in table 5.6.

Table 5.6: Iterations for 8000 kPa and gas inlet temperature of 900 °C

Steam inlet Temperature (°C)	Gas inlet temperature (°C)	Steam outlet temperature (°C)	Steam mass flow rate ms (kg/sec)	Wetness fraction X'	Power generated (KW)	Overall thermal efficiency ηoth
350	900	100	14.83354746	0.170778	10411.71915	0.273607
400	900	100	14.13677747	0.128891	10361.38242	0.272373
450	900	100	13.4934163	0.090959	10429.06128	0.274418
500	900	100	12.89754294	0.056148	10574.74608	0.278683
550	900	100	12.34410469	0.023861	10771.52938	0.284456

From the above tables, it was concluded that the maximum efficiency was obtained for a pressure of 8000 kPa, gas inlet temperature of 900 °C, steam inlet temperature of 550 °C and steam outlet temperature of 100 °C. The power generated was found to be 10.77 MW with an inlet steam mass flow rate of 12.34 kg/s and an efficiency of 28% which is close to the specified range of 40-50%. [18]

After the inlet and outlet conditions were specified, the mechanical aspect of designing was done.

The absolute velocity of steam at inlet to moving blade, i.e., exit velocity of nozzle was found using the formula $C_1 = 44.72\sqrt{\Delta h_{isen}}$ and was found to be 1279.61 m/s. To find the blade velocity, different ratios of mean blade velocity to inlet blade velocity (u/C_1) were assumed and vector diagrams were plotted as described in section 4.1 using AutoCAD. The vector plot for a ratio of 0.2 is shown in figure 5.1.

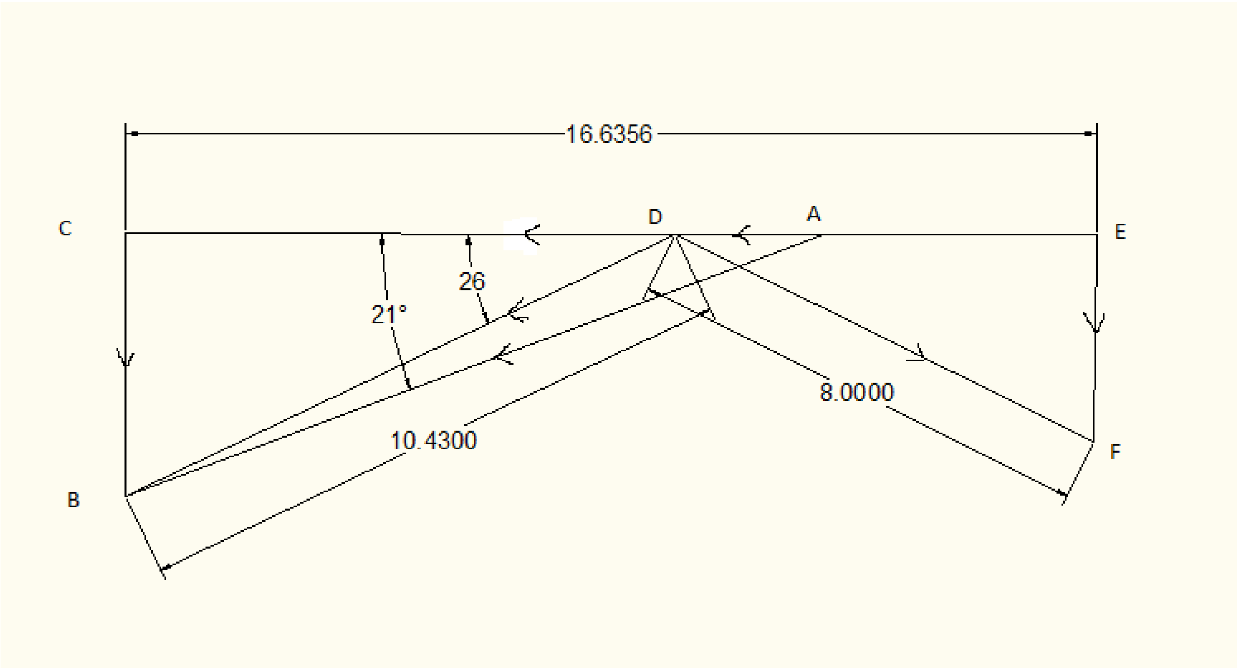

Figure 5.1: Vector plot for u/C1 ratio of 2 using AutoCAD

Similar plots were drawn for ratio of 0.3, 0.4, 0.5 and 0.6. Using these vector plots, the blade efficiency, pressure losses and subsequently the internal efficiency were found out. The results have been shown in table 5.7.

Table 5.7: Calculation of internal efficiency

S. No	u/C_1	Mean velocity, u(m/s)	$(P_{loss})/(C_1^2/2)$	η_b	η_i
1	0.2	172.2	$9.72 * 10^{-4}$	0.52	0.52
2	0.3	258. 384	$3.2 * 10^{-3}$	0.68	0.67
3	0.4	344.512	$7.7 * 10^{-3}$	0.8	0.79
4	0.5	430.64	0.015	0.76	0.74
5	0.6	516.77	0.02	0.73	0.71

To find the value of the velocity of blades, the ratio which gave the highest internal efficiency was chosen. Fig. 5.2 shows a plot of u/C_1vs internal efficiency (η_i).

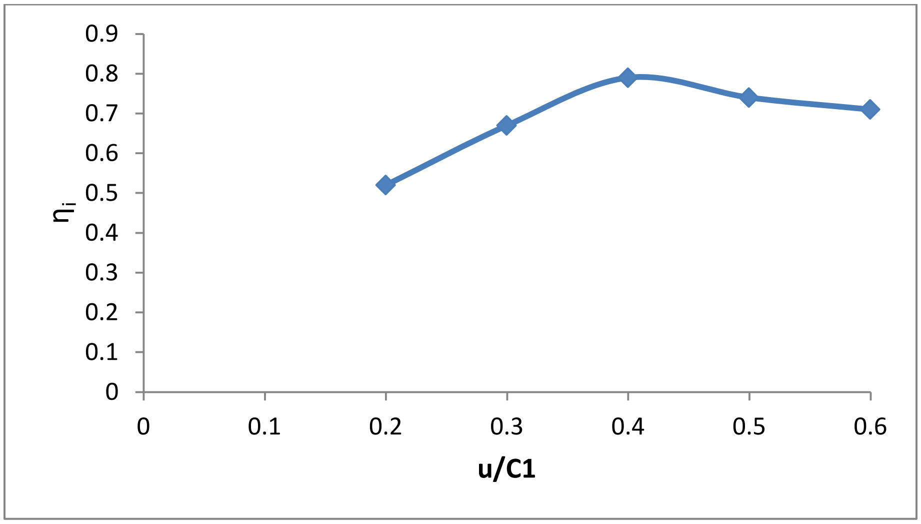

Figure 5.2: Variation of internal efficiency with ratio of mean blade velocity and inlet blade velocity

The internal efficiency was found to be a maximum for a ratio of 0.4. Using this value the blade speed was found to be 524.64 m/s.

The diameter of the disc was calculated using the formula, $u = \pi DN/60$

Where N= no of revolutions

= 3000 rpm [17]

Hence, diameter of disc was obtained as, D = 3.3 m

The nozzle efficiency was found using the formula $\eta_n = (C_1^2 - \Phi C_2^2)/\ (2(\Delta h)_{isen} *1000)$ and it came out to be 0.94.

The rim power and shaft power were then calculated, followed by stage efficiency which was 0.28.

The Reheat factor, the ratio of internal efficiency and shaft efficiency, was found to be 1.46.

The steam turbine design can be summarized in table 5.8:

Table 5.8: Specifications of Steam Turbine

Velocity at inlet to blade (C_1)	1279.61 m/s
Nozzle Angle	20°
absolute velocity of steam at outlet from the blade (C_2)	340 m/s
Relative velocity of steam with respect to the tip of the blade at inlet (C_{r1})	820 m/s
relative velocity of steam with respect to the tip of the blade at outlet (C_{r2})	656 m/s
tangential component of velocity C_1 known as velocity of whirl (C_{w1})	700 m/s
tangential component of velocity C_2(C_{w2})	60 m/s
velocity of blade (mean value) (u)	511.84 m/s
angle of blade at inlet (β_1)	31 °
outlet angle of blade (β_2)	31 °
angle made by entering steam having velocity $C_1$with tangent of the wheel at entrance of moving blade (α_1)	20 °
angle to the tangent of wheel at which C_2 leaves the	20 °

blades (α_2)	
Diameter of disc	3.3 m
carry over factor	0.9
blade velocity coefficient = C_{r2}/C_{r1}	0.8
internal efficiency	0.79
Nozzle efficiency	0.94
Blade efficiency	0.8
Shaft Efficiency	0.28
Overall thermal efficiency	0.28
Reheat Factor	1.46

5.3 COST ESTIMATION

The capital cost was found out from the cost of the equipment, i.e., boiler and steam turbine. The equipment are assumed to operate for 8000 hrs/year.

Table5.9: Annual cost estimation

Head	Cost (Rs/year)
Capital cost	$504.08 * 10^6$
Operating cost	18, 710, 698
Power consumption by equipment	130, 000, 000

The operating cost involved the cost of water required to produce steam and the maintenance cost of the equipment.

Cost of electricity produced is found to be Rs 560, 092, 000/-

The profit is the difference between the cost of electricity exported and the sum of power consumption and operating costs which is found to be Rs 411, 381, 302/-

Payback period is the ratio of the capital cost and profit, calculated as 1.22 years

Thus, payback period is less than 3 years so it is acceptable.

CHAPTER 6

CONCLUSION

In the present system, waste heat integration technique was designed to utilize the waste heat in the sponge iron production process. The salient features of the design are:

1. A waste heat recovery boiler and steam turbine is designed for heat integration.
2. Total power generation in the system is 10.77 MW with 85% and 85%isentropic efficiencies in boiler and steam turbine.
3. Overall thermal efficiency of the system is found as 28% where diameter of the turbine blades is 3.3 m.
4. The cost of the installation of the equipment is approximately Rs 504 lakhs.
5. The power generated can be exported which results in an annual profit of Rs 411 lakhs.
6. With these savings, the payback period is estimated to be 1.22 years

The design has the advantage that it utilizes the waste heat in the flue gases for generation of power which can be either put to use in the plant or can be exported.

Therefore, it is concluded that this design can be applied to sponge iron plants.

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APPENDIX A

DESIGN OF BOILER

For the design of boiler, using energy balance, we have the equation,

$$m_g C_g \Delta T g = m_s\ (\lambda + C_{p1}(T_s - T_0) + C_{p2}(T_{out} - T_s)$$

Where, m_g and m_s are the gas and steam flow rates respectively

C_g, C_{p1} and C_{p2} are the specific heats given by the formula:

C_p =1.78+ (0.107T) + (0.586T^2)-(0.2T^3) where T is the temperature in Kelvin/1000-- (1)

T_s is the saturation temperature of water at the specified pressure

T_0 is the ambient temperature

T_{out} is the outlet temperature of steam

$\Delta T_g$is the temperature difference between inlet and outlet gas temperature

The pressure and temperature in the boiler are taken as 9000 kPa and 400 °C [11]; we get T_s as 303.4°C.

Also, using (1), we get C_{p1} = 1.92 and C_{p2} = 2.02

Taking the gas inlet temperature as 850 °C and gas outlet temperature as 250 °C and assuming the heat transfer to be 85% efficient, we have,

0.85* 120.54 * 1.66 * (850-250) = m_s [1378.88 + 1.92* (303.4-25) + 2.02* (400-303.4)]

We get m_s= 56.9 t/hr = 13.43 kg/sec

APPENDIX B

ENERGY BALANCE IN STEAM TURBINE

Assuming the inlet conditions as 400 °C and 9000 kPa, the wetness fraction of steam is calculated which must be less than 0.15 [16]

From steam tables, inlet conditions at T_1= 400°C and P_1=9000 kPa are:

H_1= 3117.37 KJ/kg

S_1= 6.2876 KJ/kg.K

Turbine outlet conditions for isentropic expansion to 100°C from steam tables are:

P_2= 96.18 kPa

S_2= 6.2876 KJ/kg. K

The wetness fraction (X) can be calculated from

$S_2 = XS_L + (1-X)\, S_V$

Where S_L and S_V are the saturated liquid and vapour entropies. Taking saturated liquid and vapour entropies from steam tables at 100°C and 96.18 kPa,

$6.2876 = 1.3124 * X + (1-X)\, 7.3885$

X= 0.186

The turbine outlet enthalpy for an isentropic expansion can be calculated from

$H_2 = XH_L + (1-X)\, H_V$

Where H_L and H_V are the saturated liquid and vapour enthalpies. Taking saturated liquid and vapour enthalpies from steam tables at 100°C and 96.18 kPa,

H_2= 0.186*419.579 + (1-0.186) *2676.36

H_2= 2256.36 KJ/ kg

For a single stage expansion with isentropic efficiency of 85%

$H_2' = H_1 - \eta (H_1 - H_2)$

H_2'= 3117.37 – 0.85 (3117.37 – 2256.36)

= 2385.482 KJ/ kg

The actual wetness fraction (X’) can be calculated from:

$H_2' = X' H_L + (1-X') H_V$

Where H_L and H_V are the saturated liquid and vapour enthalpies

H_2'= 2385.482= X’*419.579 + (1-X’) *2676.36

X’= 0.12

Power generated $W = m_s (H_1 - H_2')$

= 13.43 (3117.37 – 2385.482)

= 9.84 MW

APPENDIX C

DESIGN OF IMPULSE TURBINE

The design of a single stage impulse turbine consists of the following steps:

1. Isentropic heat drop $(\Delta h)_{isen}$ is obtained using Mollier chart

   $(\Delta h)_{isen} = H_2 - H_0$

   $= 442.06$ KJ/kg

2. Velocity at the exit of nozzle $C_1 = 44.72\sqrt{\Delta h_{isen}}$

   $= 940.24$ m/s

3. The nozzle angle (α_1) is assumed to be 20°

4. Approximate internal efficiency (η_i)is found for various values of u/C_1 ranging between 0.2 – 0.6

   $\eta_i = \eta_b - \frac{(P_{loss})df,bw}{C_1^2/2}$

   Where $\eta_b = 2uC_w/C_1^2$

   $(P_{loss})_{df,bw} = \lambda[1.07\,D^2 + 0.61z\,(1-\epsilon)\,l^{1.5}]\,D\,(u/100)^3\rho$

   Here $\lambda = 1.15$ [for superheated steam]; [15]

   $\epsilon = 0.4$ [assumed] [15]

   z= no. of velocity stages, taken as 1 here

   $\rho = 2.54$ [from steam table]

   The diameter, D is initially assumed to be 2.1 m

5. Velocity C_w is found using velocity triangle as shown below:

   Firstly, a ratio of u/C_1 is assumed. Let it be 0.2 here.

Hence we have, u= 0.2 * C_1 = 255.9 m/s

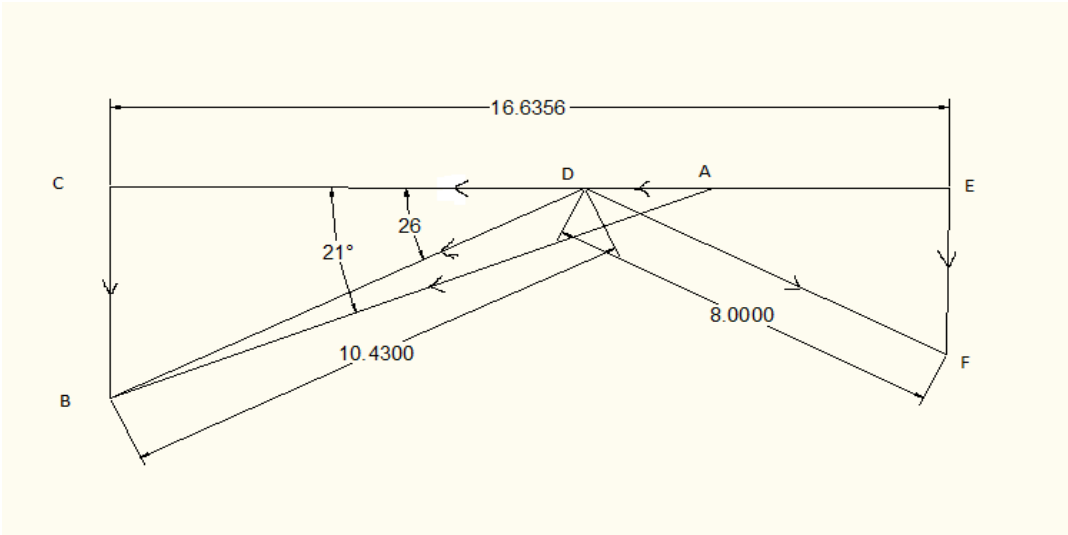

Figure C.1: Velocity diagram for u/C1 of 0.2

From the velocity diagram, we have:

C_{r1}= 1043 m/s

C_{r2}= k *C_{r1} = 0.8 * 1043 = 834 m/s

C_w= 1663 m/s

η_b= $2uC_w/C_1^2$

= (2*255.9* 1663)/ 1279.61^2

= 0.52

Now, $(P_{loss})_{df,bw}$= $\lambda[1.07 D^2 + 0.61z (1-\epsilon) l^{1.5}] D (u/100)^3\rho$

= $4.72 *10^{-5} u^3$

= 788.17 W

Therefore we have, $\eta_i = \eta_b - \frac{(P_{loss})df, bw}{C_1^2/2}$

$= 0.52 - 9.72*10^{-4}$

$= 0.51$

Similarly, step 5 is repeated for different ratios of u/C_1. The values of internal efficiency are plotted against u/C_1. The ratio giving the highest value of internal efficiency is chosen as the optimum value.

6. $u = (u/C_1)_{optimum} * C_1$

   $= 0.4 * 1279.61$ m/s

   $= 524.64$ m/s

   For diameter of the disc,

   $u = \pi DN/60$

   Where N= no of revolutions

   = 3000 rpm

   Hence, diameter of disc, D = 3.3 m

7. Nozzle efficiency, $\eta_n = \frac{C_1^2 - \varphi\, C_2^2}{2\,(\Delta h)_{isen}}$

   $= 0.94$

8. Stage efficiency η_s :

   Isentropic power $= m_i * (\Delta h)_{isen}$

   = 12.2 MW

9. Rim power= $\frac{(m_i - m_g) * C_w * u}{1000}$

   =9.83 MW

10. Shaft power = Rim power – losses

= 3.5 MW

11. Stage efficiency = shaft power/ isentropic power

= 0.28

12. Reheat factor = internal efficiency/ stage efficiency

= 1.46

APPENDIX D

COST ESTIMATION

The capital cost was found out from the cost of the equipment, i.e., boiler and steam turbine. The equipment are assumed to operate for 8000 hrs/year

Capital cost = Cost of boiler + cost of steam turbine

= Rs 46, 800/KW [18]

= Rs 504.08 * 10^6 /-

The operating cost involved the cost of water required to produce steam and the maintenance cost of the equipment

Cost of water = Volume of water * Cost of water/1000 L [19]

= 211. 01 * 10^6 l/yr * Rs 7/ 1000 l

= Rs 14, 77, 098/-

Maintenance cost of turbine = Rs 0.2/ KWh [18]

= Rs17, 233, 600/-

Total operating cost= Cost of water + maintenance cost

= Rs 18, 710, 698/-

Cost of electricity produced = Rs 6.5/KWh

= 6.5 * 10771 KW* 8000 hrs/yr

= Rs 560, 092, 000/-

Rating of steam turbine is 2.5 MW [20], hence

Power consumption by equipment = 2500 * 8000 hrs/yr

= 20, 000, 000 KWh

Cost of power consumed = 20, 000, 000 * Rs 6.5/KWh

= Rs 130, 000, 000/-

Profit= cost of electricity exported – power consumption – operating costs

= 560, 092, 000 – 130, 000, 000 –18, 710, 698

= Rs 411, 381, 302/-

Payback period = Capital cost/ Profit

= 1.22 years